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AN INVESTIGATION OF VERY-HIGH-SPEED-DROP-IMPINGEMENT EROSION OF 1100 ALUMINUM

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The results of inspection of the eroded specimens with use of a light microscope and scanning electron microscope revealed that plastic flow of the aluminum increased as the test velocity increased Cross-sectional cuts of the specimens revealed a small amount of work-hardening at velocities of Mach 2.5 and above, but no evidence of crack formation was found. These findings are compatible if the heat generated by the amount of plastic flow of aluminum that occurs is large enough to anneal the worked metal. If this is the case, aluminum is a permanently plastic material.

Two mechanisms of metal removal are considered. The first, which is applicable at velocities up to Mach 2.5, is the breaking off of protuberances formed by plastic flow of the metal. The second, which is applicable at velocities above Mach 2.5, is the extrusion of separate masses of metal which have become surrounded by surfaces of discontinuity as a result of the pummeling effect of the individual waterdrop blows. The second mechanism of metal loss can be expected to progress as a layer-removal process.

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FOREWORD

This report was prepared by the University of Dayton Research Institute, Dayton, Ohio, under Air Force Contract F33615-69-C-1385. It was initiated under Project No. 7340 "Nonmetallic and Composite Materials", Task No. 734007 "Coatings for Energy Utilization, Control and Protective Functions". The work was administered under the direction of the Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, with George F. Schmitt, Jr. of the Elastomers and Coatings Branch, Nonmetallic Materials Division, acting as project engineer.

This report covers the work carried out during the period from July 1970 through February 1971.

This report was submitted by the author in April 1971.

This technical report has been reviewed and is approved.

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ABSTRACT

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The results of inspection of the eroded specimens with use of a light microscope and scanning electron microscope revealed that plastic flow of the aluminum increased as the test velocity increased. Cross-sectional cuts of the specimens revealed a small amount of work-hardening at velocities of Mach 2.5 and above, but no evidence of crack formation was found. These findings are compatible if the heat generated by the amount of plastic flow of aluminum that occurs is large enough to anneal the worked metal. If this is the case, aluminum is a permanently plastic material.

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SECTION I

A STUDY OF VERY-HIGH-SPEED DROP-IMPACT EROSION OF 1100 ALUMINUM

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1. INTRODUCTION

In work reported over fifteen years ago [1, 2], parallel studies were used to shed light on the mechanism by which high-speed waterdrop impacts are able to produce erosion of aluminum and of poly (methyl methacrylate). It was found that an impinging waterdrop has two damage-producing attributes: the impact pressure that it exerts and the high-speed flow of the liquid contents of the drop. It was concluded that the erosion damage that is produced on any material by high-speed waterdrop impingement is a consequence of these impact properties of a waterdrop.

This background information was used in studying the mechanism of waterdrop-impact erosion of commercially pure 1100 aluminum and of 3003 aluminum at a velocity of 880 ft/sec in a 1-inch per hour rain density (average drop diameter 1.9 mm) and of single waterdrop impacts against commercially pure aluminum at velocities in the range of 1384 to 2700 ft/sec (drop diameter 2 mm). A summary of the results of this early study of the mechanism of drop-impact erosion of aluminum follow.

1.1 Results of Early Research on the Mechanism of Drop-Impact Erosion of Aluminum

The initial stage of erosion for specimens tested at 880 ft/sec was observed to be a barely perceptible roughening, dulling, or frosting of the specimen surface. Two types of damage were found in the frosted aluminum surface[1]. One type of damage was shallow dents; shallow dents

were found both for 1100 and for 3003 aluminum. On the basis of evidence presented, it was concluded that these dents are formed by single waterdrop impacts; they are the result of plastic flow of aluminum as a consequence of the impact stresses imposed. The other type of damage in the initial roughening of the surface was well developed pits. Four observations were made with regard to these pits: the pits had a wide distribution in size, the population density of the pits was comparable to that of residual pit blemishes in an area shielded from drop impingement; the population density of the pits did not show a consistent increase with increase in test time; the population of these initial pits was smaller on a highly polished specimen than on a dull polished specimen. On the basis of these observations it was concluded that these initial pits were residual pit blemishes in the surface of the specimen before test which had become enlarged as a consequence of drop impingement. Such residual pit blemishes serve as pressure-raisers[3].

With increase of test time and of number of impacts sustained, a hill-and-valley structure developed over the impingement area of 1100 aluminum specimens due to the pummeling action of the impinging drops against this soft metal; 3003 aluminum, which is harder than 1100 aluminum, did not develop a noticeable structure of this kind. This is an example of the effect of small differences in the properties of materials.

The damaging action of the impact pressure exerted by the impinging drops was accompanied by the damaging action of the fluid flow of the drop liquid. Etching of the aluminum specimens as a consequence of the fluid flow of the impinging drops was observed[1]; the extent of etching increased with elapsed test time. The character of the etching is different for 1100 and for 3003 aluminum. In the case of 1100 aluminum, the etching consisted of grooves rather than pits; the grooving was most pronounced in the valleys of the uneven hill-and-valley surface that formed on 1100 aluminum specimens as drop impingement progressed. In the case of 3003 aluminum, the etching consisted of uniform shallow pitting that resembled shot-peening. This is another example of the effect of small differences in the properties of materials.

The etching was regarded as being both chemical and mechanical in origin[1]. The chemical contribution was considered to have at least two sources: the hydrogen and hydroxyl ions that are generated during a high-speed waterdrop impact[4] and the electrochemical potential difference associated with the velocity gradient in the rapidly moving water. The mechanical contribution was ascribed to the shear stress exerted against the surface of the aluminum by the rapid water flow and to the torque that this flow exerts against surface protrusions that are restrained by the underlying metal. Within the limits of the study that was made, it appeared that the mechanical contribution is the more important.

It was pointed out[1] that the etching of 1100 and of 3003 aluminum appears to advance to a point where the etch grooves (or pits) themselves become pressure-raisers. When this point is reached, a burst of erosion craters suddenly nucleates in the etched surface and the entire surface rapidly becomes a mass first of adjacent and then of overlapping craters[1].

The mode of metal loss for aluminum under drop impingement was considered[1]. The interior walls of well developed craters were observed to have a high degree of reflectivity and to appear white when inspected with a light microscope. Black markings were observed in these white areas and it was thought that these black markings might be cracks or small areas where metal had already broken away. It was postulated that the impact pressure of impinging drops, which is multiplied within pits, may work-harden, embrittle, and crack the metal at the bottoms of pits and that pieces of metal may eventually be dislodged between circumscribing cracks[1]. It was postulated further that when drops strike into pits the shear stress exerted by the very rapid flow of drop liquid up the pit walls, and the torque that this fluid flow exerts against protrusions that are restrained by underlying metal, may introduce new cracks and/or widen cracks that already existed.

Since the time that this early work was reported, Rieger[5] has pointed out that the black markings at the bottoms of pits in aluminum are not cracks. With use of the electron microscope, he has observed that

these black markings are ripples in the metal and he has postulated a metal-loss mechanism for aluminum that involves the shearing off of these protruding ripples of metal. The concept of the shearing away of metal that protrudes above a surface that is being exposed to drop impingement is not new; the shearing off of a surface protrusion by a mass of flowing liquid has been discussed[6]. For materials of substantial strength this type of metal loss has been associated with the small losses that occur during the incubation period. If the black markings at the bottoms of pits are not cracks, the mode of metal removal that involves crack formation, crack growth. and crack intersection cannot be accepted for aluminum until evidence for the existence of cracks in an eroded aluminum specimen is found. If the shearing off of protrusions is a principal mechanism of metal loss, this needs to be established and this mechanism of loss needs to be investigated further.

The study that was made[1] at velocities from 1384 to 2700 ft/sec was restricted to single impacts. These impacts produced craters in 1100 aluminum. The crater produced by impact of a 2-mm waterdrop at a velocity of about 2500 ft/sec was found to be comparable with the crater produced by a steel sphere impact against aluminum at a velocity of 900 ft/sec. It was concluded that at velocities of about 2500 ft/sec a waterdrop acts as a Brinell ball toward this soft metal[1]. Evidence of the flow of the drop liquid during these high-speed impacts was cited[1] and the importance of the shearing action of this flow was pointed out. The craters produced by waterdrop impacts at velocities from 1384 to 2700 ft/sec do not have the highly polished walls of craters produced by impacts of steel spheres; inside walls of the high-speed waterdrop craters are etched with flow grooves.

It was pointed out[1] that the mechanism of damage of aluminum produced by waterdrop impingement below 1000 ft/sec may be categorized as microscopic and that above 1000 ft/sec as macroscopic on the basis of the role of surface defects. At impact velocities below 1000 ft/sec the presence or absence of surface defects, which act as pressure-raisers, is important in determining the extent of erosion damage that will be produced. At

velocities above 1350 ft/sec, a crater is produced by each drop impact irrespective of the presence or absence of surface defects.

1.2 Results of a Recent Study of Drop-Impact Erosion of Aluminum

Recently, a study of drop-impact erosion of 1145 aluminum has been reported[7]. Specimens were tested at 730 ft/sec in a 2-inch per hour rain density (average drop diameter 2 mm) and at 1120 ft/sec in a 1-inch per hour rain density (average drop diameter 1.8 mm). The type of aluminum (1145) that was used for the study is an even purer form of aluminum than commercially pure 1100 aluminum. Although the reported yield strengths of the two metals are the same[8], the ultimate strength of 1145 aluminum is slightly lower than that of 1100 aluminum (13,000 psi in comparison with 15,000 psi) and 1145 aluminum is softer than 1100 aluminum.

In the light of these differences in properties, and in the light of the reported findings of the earlier study[1], it would be expected that in the first surface roughening or frosting that is produced by waterdrop impingement, the shallow dents formed by individual drop impacts should be very evident and that the first population of pits (which are produced when drops impinge against residual surface blemishes) should be very well developed and have pronounced lips of plastically flowed metal. On the basis of the work on aluminum already reported[1], etching of 1145 aluminum would be expected to take the form of grooves rather than of craters that resemble shot peening and erosion pitting would be expected to nucleate in the etch grooves.

The initial roughening or dulling of the surface was reported[7]. The existence in this roughened surface of dents produced by individual drop impacts and of the initial population of pits developed from residual surface blemishes were either not observed or not reported although, in a later section of report of this work, it is stated parenthetically that a single drop makes a negligible impression at the impact speeds considered. The grooved type of etching was apparently observed because the etch grooves were described as "angling" into the surface. No analysis of the etching

process was made but the development of pit formation was described qualitatively.

The new information for the mechanism of drop-impact erosion of aluminum that came out of this study is associated with two additional techniques that were employed. One of these additional techniques is the progressive determination of the weight lost by a specimen per increment of test time; the other is the use of cross-sectional cuts through the test specimens.

Weight-loss-versus-time plots were presented but no analysis was made of them. Inspection of the weight-loss-versus-time plots for the two sets of test conditions that were employed is quite informative. The configuration of the test points indicates that the same statistics that have been applied to other Class A metals[4] can be applied to pure aluminum. The first riser (knee) in the staircase-shaped plot occurs after 15 minutes of test at 730 ft/sec and after about 10 minutes of test at 1120 ft/sec. Because the elapsed test time (or number of impacts sustained) is related to the statistical probability of a damage-producing hit[4], this is experimental evidence that the statistical probability of a damage-producing hit is a function of impact velocity; this would be expected.

The slope of the first riser in the staircase-shaped plot is a measure of the maximum rate at which erosion occurred and the width of the weight-loss plateau that follows the first riser is a measure of the time required for the removal of the first layer of metal from the test specimens[4]. The number of data points collected for the higher of the two test velocities used is too small to make it possible to compare either of these two quantities for these test velocities. It is noteworthy that the first weight-loss plateau in the weight-loss-versus-time plots occurs at the same value of weight loss for both velocities used. This indicates that the size of the eroded particles is essentially the same during the removal of the first layer of metal from the specimens at the two velocities used[4].

The data collection was not carried far enough to establish the weight loss that must be associated with the second weight-loss plateau which is associated with the removal of the second layer of metal from the

test specimens. However, from the meager data presented, it can be seen that the height of the second riser of the staircase-shaped plots will be much higher for the higher test velocity used. This indicates a marked increase in eroded particle size for the higher velocity[4].

The existence of cracks at the end of 10 minutes of test at 730 ft/sec was cited[7] but the evidence pointed out is meager. Micrographs of cross sections of specimens that were tested for 15 minutes appear to show evidence of crack formation. An elapsed time of 15 minutes corresponds with the position of the first riser in the staircase-shaped plot of weight loss against test time. This leads to the tentative conclusion that a significant weight loss may be associated with crack formation, but, because the supporting evidence is meager, this needs to be substantiated.

From the evidence just given it would be expected that crack formation should be evident at the end of 10 minutes of test at 1120 ft/sec because 10 minutes corresponds with the position of the first riser in the weight-loss-versus-time curve for this velocity. However, from the micrographs given there appears to be little or no evidence of crack formation in the cross section of a specimen tested for 10 minutes at 1120 ft/sec.

The difficulty may be inherent in the rotating-arm device that was used to test the specimens. Although the test chamber of this device is partially evacuated, it operates at a substantial fraction of one atmosphere of pressure. It is possible that the air masses being pushed along by the rotating specimens are of sufficient thickness to fragment the drops. If this is occurring, it can be expected that it will affect the character of the erosion produced. This could be checked by testing an 1145 aluminum specimen for 10 minutes with the test chamber evacuated to the vapor pressure of water and by looking for cracks in a cross-sectional cut of this specimen. On the other hand, it is possible that 1145 aluminum does not develop cracks at a test velocity of 1120 ft/sec.

SECTION II

2. INSPECTION OF 1100 ALUMINUM SPECIMENS TESTED AT VERY HIGH VELOCITIES

A number of specimens of commercially pure aluminum were tested under waterdrop impingement at velocities up to 4202 ft/sec with use of the rocket-sled and test-track facility at Holloman Air Force Base, New Mexico, in a joint Air Force-Navy program on the evaluation of materials for high-speed rain ~rosion resistance[9]. The specimens were mounted on the rocket sled in such a way that they received waterdrop impacts at angles from 13.5 to 90 degrees.

The rocket sled ran for a distance of 6000 ft through an artificial rain of tap water. The mean drop size of this rain was 1.9 mm and the rain rate over the test run was 2.5 inches per hour. The velocities at which specimens were carried through this rain field by the rocket sled ranged from 1635 to 4202 ft/sec. Polyethylene bags filled with water were used to decelerate the rocket sled at the end of a run; a brown polyfoam was also used for this purpose.

The specimens were 1.25-inch squares cut from a composite sheet which consisted of two 0.125-inch sheets of commercially pure aluminum bonded together with epoxy adhesive. The specimens were held in place with use of restraining frames. The surface area against which the drops impinged within the restraining frame on each specimen was a 1-inch square. No special surface finishing or polish was given to the specimens. These tested specimens were made available for study by Mr. George F. Schmitt, Jr., of Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio.

At the highest test velocity that was used, the bow shock in front of those specimens that were mounted at an angle of 90 degrees to the direction of motion of the sled and the air flow behind this shock prevented the drops from impinging. In order to include tested specimens for all of the velocities at which tests were run, the study that was undertaken was restricted to specimens that received waterdrop impacts at an angle of 60 degrees. These

specimens, which are shown as a group in Figure 1, were studied with use of the light microscope, the scanning electron microscope, and with the use of metallographic techniques. The test conditions for these specimens are given in Table 1. The results of the studies that were made are described in the following sections of this report. Throughout these studies it was found that a full quota of drop impingement did not occur even on the specimen mounted at an angle of 60 degrees for the highest test velocity used.

2.1 Inspection with the Light Microscope[a]

It can be seen by inspection of Figure 1 that the damage done to the specimens increased sharply as the test velocity was increased. The specimens were studied in order of increasing impingement velocity.

The surface of the specimen tested at a velocity of 1635 ft/sec is shown at 3.5X magnification in Figure 2. Inspection of the impact surface of this specimen with a low-power binocular microscope produced four observations: (1) The impact surface is uneven; it has a hill-and-valley structure. (2) The uneven surface is lightly abraded. (3) There is evidence of a brown deposit which is not removed by washing the specimen in a stream of deionized water. (4) The impact surface of the specimen is scratched. Details of these observations are discussed below.

The most prominent feature of the impact surface of this specimen is the hill-and-valley structure that developed during the test run. As in the case of specimens tested at 880 ft/sec[1], this resulted from the punching action of the impinging drops as they were intercepted by the specimen during its flight through the rain field. Depressions in the surface of the specimen, which appear to have been produced by single drop impacts, can be seen. Some of these are indicated with arrows on the left-hand-side of the photograph shown in Figure 2. Each drop imprint consists of a shallow depression encircled by a raised ridge of metal. The visibility of the drop

[a] All of the low-magnification photographic work for the light microscope studies was done by Mr. Richard L. Fusek of the Research Institute of the University of Dayton.

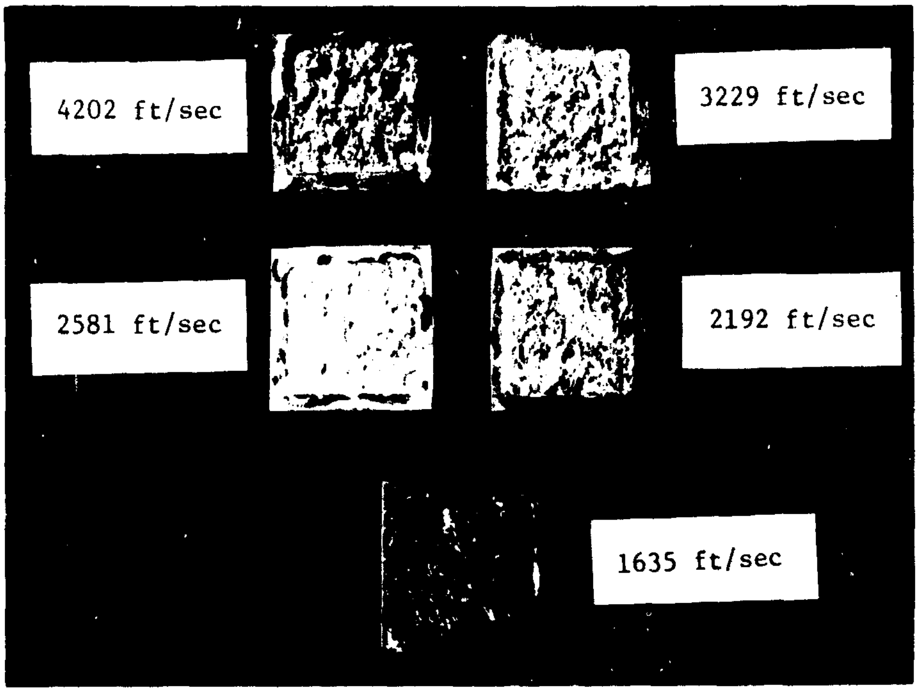


Figure 1. Specimens Tested At An Angle Of 60°. Magnification 0.7 X.

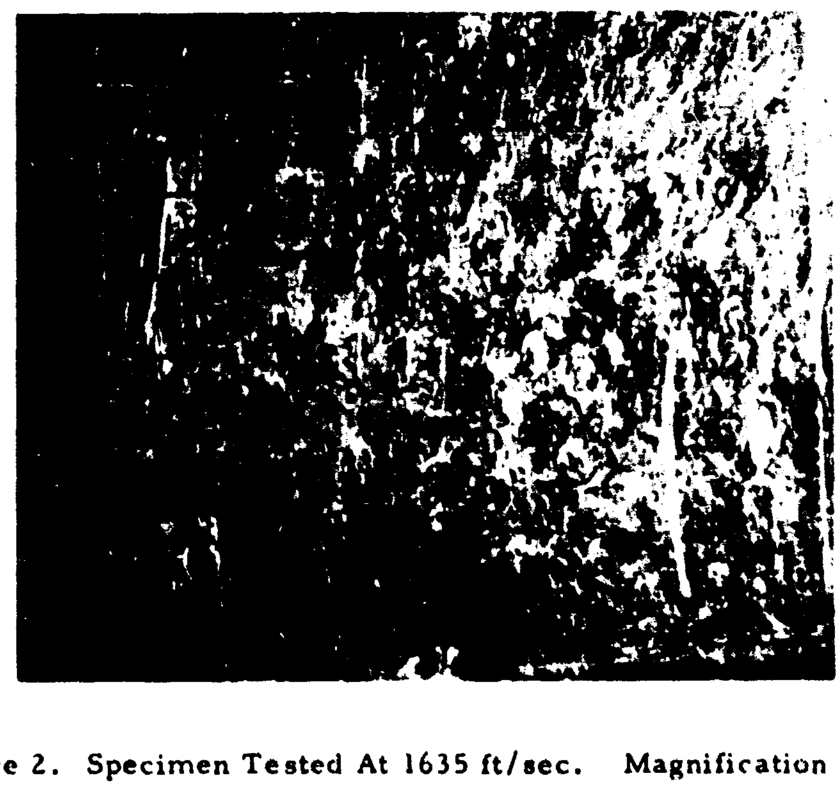


Figure 2. Specimen Tested At 1635 ft/sec. Magnification 3.5 X.

TABLE 1

Test Conditions for the Specimens that Were Studied

Rain Rate .... 2.5 inches/hour

Mean Drop Diameter .... 1.9 mm

Test Velocity[a] ft/sec	Test Time sec
4202	0.476
3229	1.858
2581	2.325
2192	2.737
1635	3.674

[a] The accuracy of the velocity measurements was ± 0.5 ft/sec.

imprints is enhanced by the fact that the raised metal around the depressions is lightly abraded. The presence of this abrasion, which can also be seen on the reverse side of the specimen, suggests that although no special surface finishing was required for the specimens, they may have been lightly polished with a fine abrasive cloth or paper when they were cut. Metal was pushed up radially around points at which drop impacts occurred but the surface abrasion was not obliterated either by the movement of the metal or by the flow of the drop liquid.

The brown deposit on the impact face of the specimen, which could not be removed by washing the specimen in a stream of deionized water is very probably impacted polyfoam because brown polyfoam was used to decelerate the rocket sled. Evidence that this may indeed be polyfoam is cited in Section 3 below.

The scratches that exist on the impact face of this specimen were compared with the scratches that exist on that part of the impact face that was covered by the restraining frame during the test; they were also compared with scratches that exist on the reverse face of the specimen. From this comparison it appears that most of the scratches probably existed prior to the test. The very prominent scratch at the right side of the photograph shown in Figure 2 either existed prior to the test run or was produced by the impact of a solid particle during the test run. The latter possibility seems to be less probable than the former because there is no crater at either end of this scratch which could be identified with the impact of a solid particle. There are, however, several other less prominent scratches that are associated with terminal craters and this evidence suggests that at least some of the existing scratches may have been produced by the impact of solid particles.

The right-hand side of this specimen (see Figure 2) appears to have received more drop impacts than the left-hand side. The surface of the right-hand side has developed a more pronounced unevenness and evidence of single-drop imprints is essentially obliterated.

The surface of the specimen tested at a velocity of 2192 ft/sec is shown at 3.5X magnification in Figure 3. Most of the observations made on the specimen tested at a velocity of 1635 ft/sec apply also to this specimen but on this specimen they are more pronounced. An exception to this statement is provided by the absence of individual drop imprints; these seem to have been obliterated by additional impacts of drops.

There is much more evidence of the brown deposit which is considered to be impacted polyfoam. If the brown deposit is polyfoam, which was used to decelerate the rocket sled, a heavier residual deposit would be expected on this specimen both because the relative impact velocity between the specimen and the polyfoam was higher and because the surface of this specimen was roughened to a greater degree during test than that of the specimen tested at a velocity of 1635 ft/sec.

Small craters were observed during inspection with the binocular microscope. These craters appear to have been caused by impacts of solid particles during the test run because scratches, which may be due to the drag of a solid particle after impact, extend from them. An example of these scratches is shown in Figure 4.

The pattern of light abrasion can be seen on the surface of the metal that was covered by the restraining frame as well as on the reverse side of this specimen. This is in agreement with the tentative conclusion that, although no surface preparation was required for these specimens, they may have been lightly abraded with a fine abrasive cloth or paper. The scratch at the right hand side of Figure 3 extends into the part of the specimen that was covered by the restraining frame; consequently, this scratch existed before the specimen was tested.

The fact that high spots in the area of the specimen that was exposed to drop impingement are marked with a pattern of light abrasion and the fact that original polish scratches can be seen in the low areas suggest that the surface unevenness was produced <u>without</u> loss of metal. This is substantiated by the weight-loss data supplied for the specimens (see Table 2, Pg. 36).

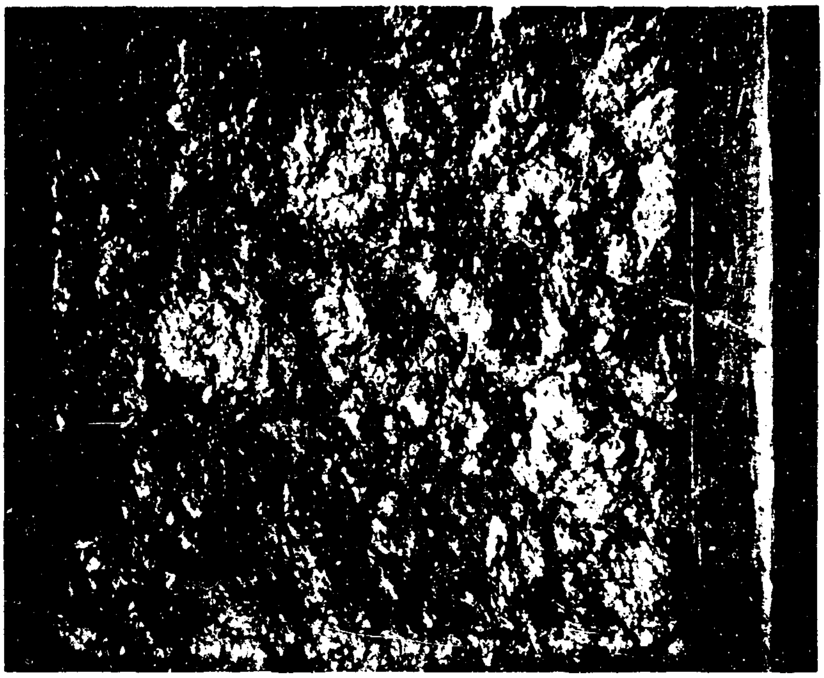


Figure 3. Specimen Tested At 2192 ft/sec. Magnification 3.5 X.

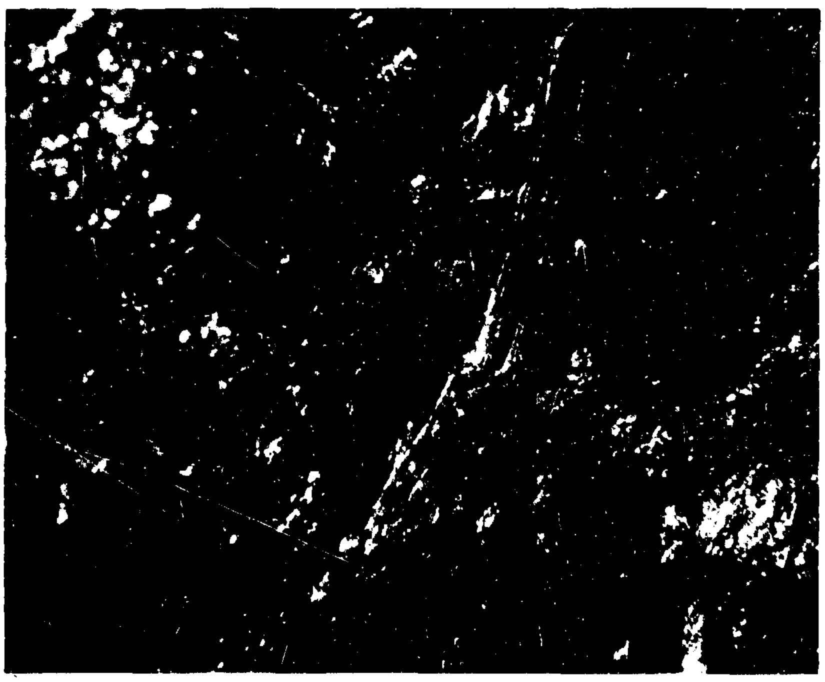


Figure 4. Possible Solid-Particle Damage. Test Velocity 2192 ft/sec.

Grooves, which appear to have been formed by the flow of liquid, can be seen at the bottoms of pits or deep depressions. Ridges of plastically flowed metal have started to form between the areas that received the most impacts. This evidence indicates that flow of the liquid contents of the impinging drops was capable of producing plastic flow of the aluminum test plate.

The outstanding feature in the appearance of the specimen tested at 2581 ft/sec in comparison with the specimen tested at a velocity of 2192 ft/sec is the marked degree to which the aluminum has flowed plastically. By viewing the specimen edge on, it can be seen that mounds of metal have been forced up above the original surface of the specimen. The tops of these mounds of metal are as smooth as if the metal had been melted; the process that occurred is probably not melting, however, but a drastic form of plastic flow.

Structures were observed in the metal where the restraining frame had held the specimen; these may or may not be cracks. Strands of plastically drawn metal exist which strongly suggest that one of the mechanisms of metal loss could be a process in which protruding strands of flowed metal either neck off in sections or are pinched off.

The outstanding feature in the appearance of the specimen tested at 3229 ft/sec is again the marked plastic flow that has occurred; the surface of the specimen is shown at 3.5X magnification in Figure 5. Large masses of metal have been moved in plastic flow; in some cases the movement has been such as to close the mouths of deep craters. Examples of sheets and filaments of flowed metal exist. Structures can be seen that could be cracks; these structures may, however, be interfaces between masses of flowed metal.

There are many mounds of plastically flowed metal which protrude above the original surface of the specimen. Figure 6 shows a view of the line of demarcation between the eroded area and the region near the specimen edge which was covered by the restraining frame. The light is

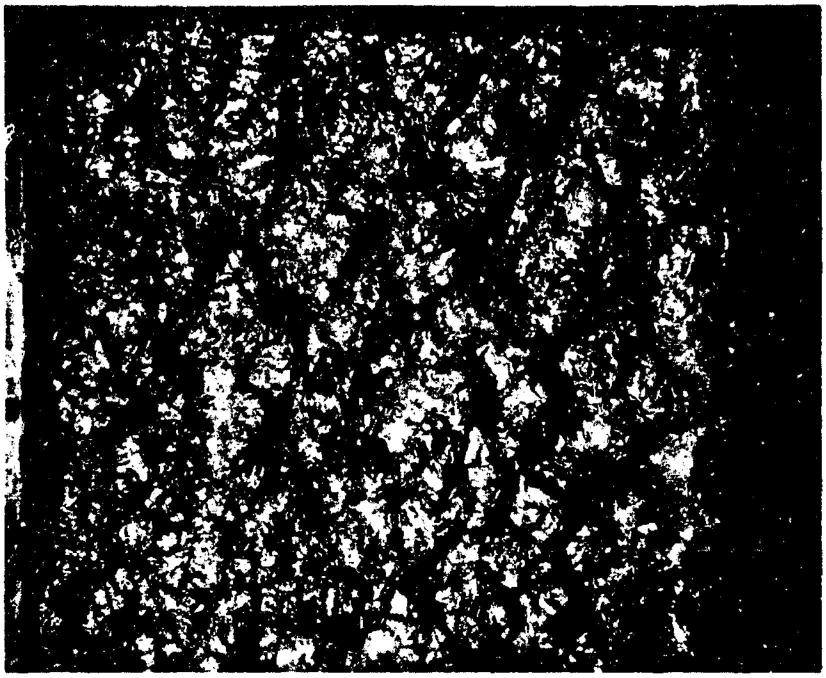


Figure 5. Specimen Tested at 3229 ft/sec. Magnification 3.5 X.

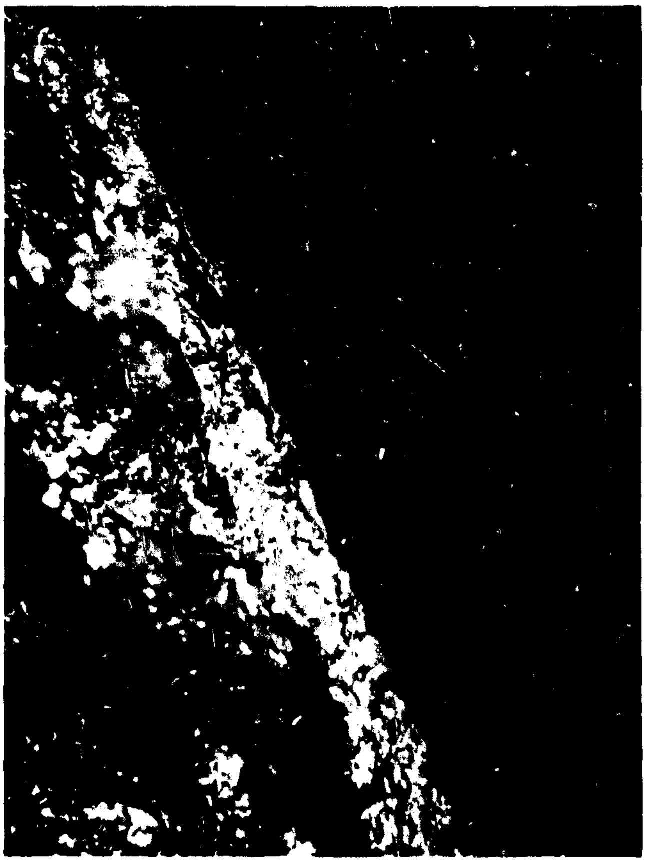


Figure 6. Flow Of Metal Against Supporting Frame. Test Velocity 3229 ft/sec.

coming from the lower left-hand corner in this picture. The height to which metal flowed up against the restraining frame can be roughly assessed from the length of the shadow that it casts.

The strong plastic flow that occurred on the specimen tested at 4202 ft/sec can be seen from the surface view of this specimen which is shown at 3.5X magnification in Figure 7 and from the edge-on view shown in Figure 8. From Figure 8 it can be seen that plastically flowed metal has been stacked up above the original surface of the specimen to a height that is close to one fourth of the specimen thickness. Craters exist that extend through the entire thickness of the specimen but, in general, the structure of the plastic flow of metal on this specimen appears to be somewhat less drastic than that on the specimen tested at 3229 ft/sec.

An outstanding feature in the appearance of this eroded specimen is that it is strongly darkened in comparison with the other specimens. The extent of this darkening can be appreciated by comparing the reflectivity of the eroded specimen surfaces shown in Figures 5 and 7. The darkening of the specimen tested at a velocity of 4202 ft/sec suggests that it was subjected to a strong rise in temperature.

Another feature of this specimen is that there are many small black spots on the bottoms and side walls of deep craters. These black spots appear to be black deposits rather than holes. It is conceivable that the temperature reached by this specimen during its test run was high enough to carbonize polyfoam that struck the face of the specimen during the deceleration of the rocket sled.

2.2 Inspection with the Scanning Electron Microscope[b]

When the specimen tested at a velocity of 1635 ft/sec is inspected with the naked eye or with a low power binocular microscope, the

[b] Study of the tested specimens with use of a scanning electron microscope was carried out with the assistance of Dr. Richard S. Harmer of the Research Institute of the University of Dayton.

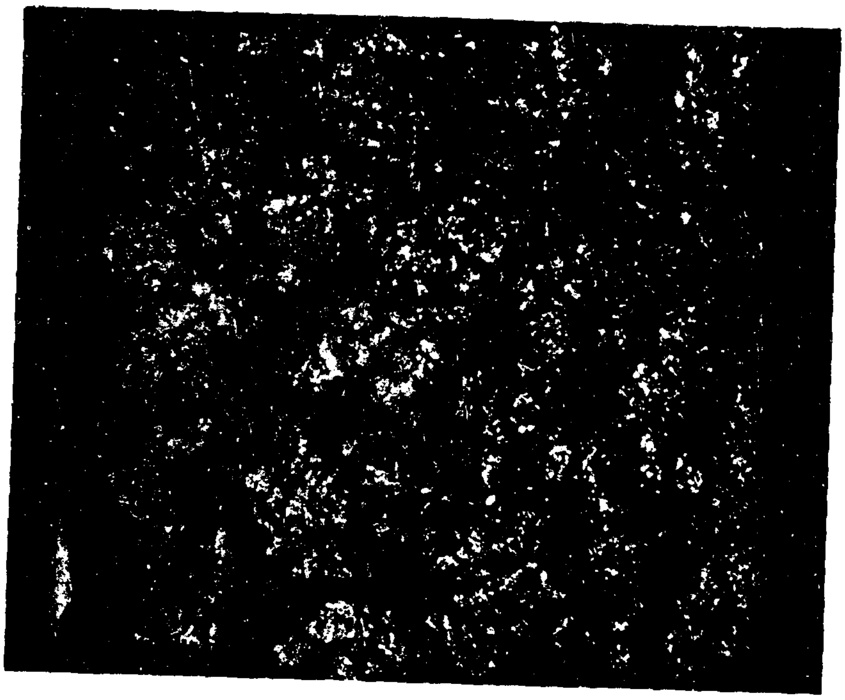


Figure 7. Specimen Tested at 4202 ft/sec. Magnification 3.5 X.

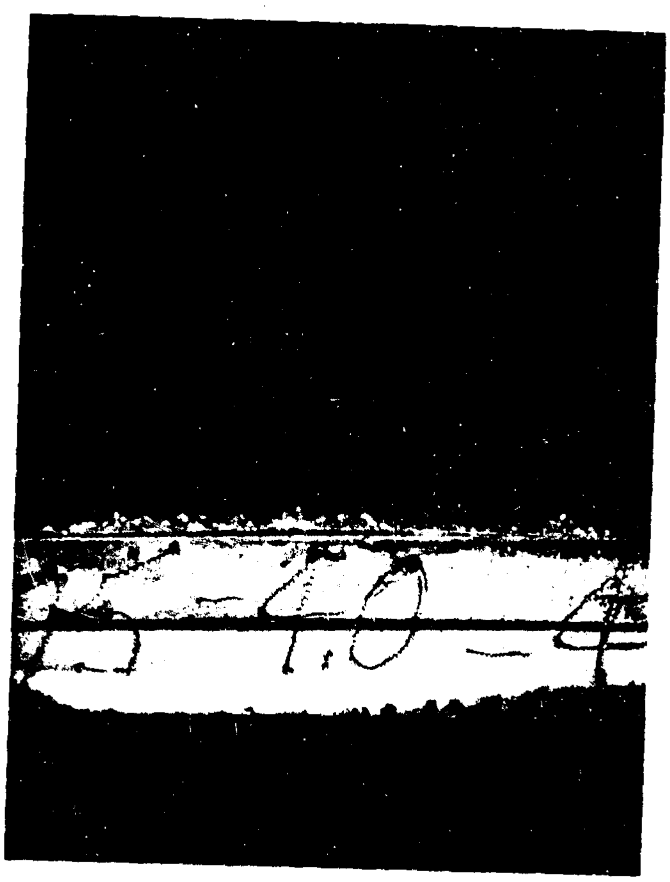


Figure 8. Edge View Of Specimen. Test Velocity 4202 Ft/sec.

presence of the shallow dents, which have provisionally been identified with single impact sites, is observed. Inspection with use of a scanning electron microscope provided no new information about these wide shallow dents because the minimum magnification that could be used was too high to see them. However, evidence of the initiation of plastic flow along the rolling structure of the metal sheet from which the specimens were cut was observed. An example of this is shown in Figure 9. The shear stress exerted by a flowing liquid against a level surface is small. It appears that ridge elevations in the rolling structure of metal, however, provide restraints along which sufficient shear stress develops to make plastic flow of the metal, as a consequence of radial flow of water from impinging drops, possible.

A second example of this initial phase of plastic flow is shown in Figure 10. This view is from the surface of the specimen that was tested at an average velocity of 2192 ft/sec. Clear evidence of damage due to solid-particle impact was also found on this specimen. A view of a trench dug by an impinging solid particle, as well as the particle itself, which was trapped by the flow of the aluminum metal, is shown in Figure 11.

Severe plastic flow of the aluminum was produced on the specimen tested at an average velocity of 2581 ft/sec. A view of this at 100X magnification is shown in Figure 12. Clearly, protruding structures of flowed metal, such as the one shown near the center of Figure 12 can be sheared or pinched off by a succeeding impact and can constitute a source of weight loss for the specimen.

Examples of plastic flow of aluminum metal on the specimen tested at an average impact velocity of 3229 ft/sec are shown in Figures 13 and 14. The protruding prong of aluminum shown in Figure 13 is another example of metal which may be broken away from the specimen by a succeeding impact. The leaf-like sheet of metal shown in Figure 14 may have been drawn out by the high-speed flow of water from the impinging drops and then bent back. The thinness of this sheet can be surmised by inspecting its edges.

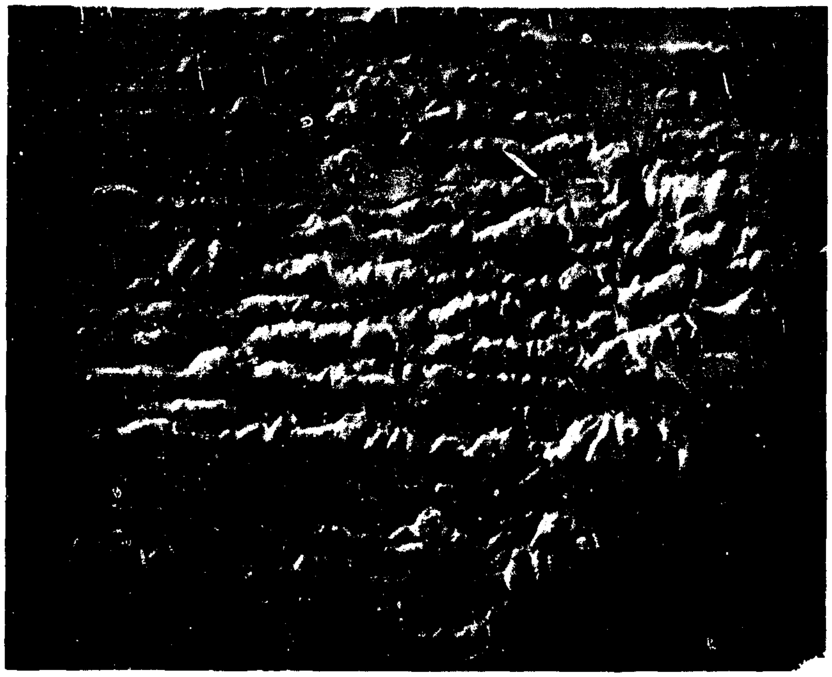


Figure 9. Initial Stage Of Plastic Flow. Test Velocity 1635 ft/sec Magnification 100X.

Figure 10. Initial Stage of Plastic Flow. Test Velocity 2192 ft/sec Magnification 100 X.

Figure 11. Solid-Particle Impact. Test Velocity 2192 ft/sec Magnification 200 X

Figure 12. Plastic Flow. Test Velocity 2581 ft/sec. Magnification 100 X.

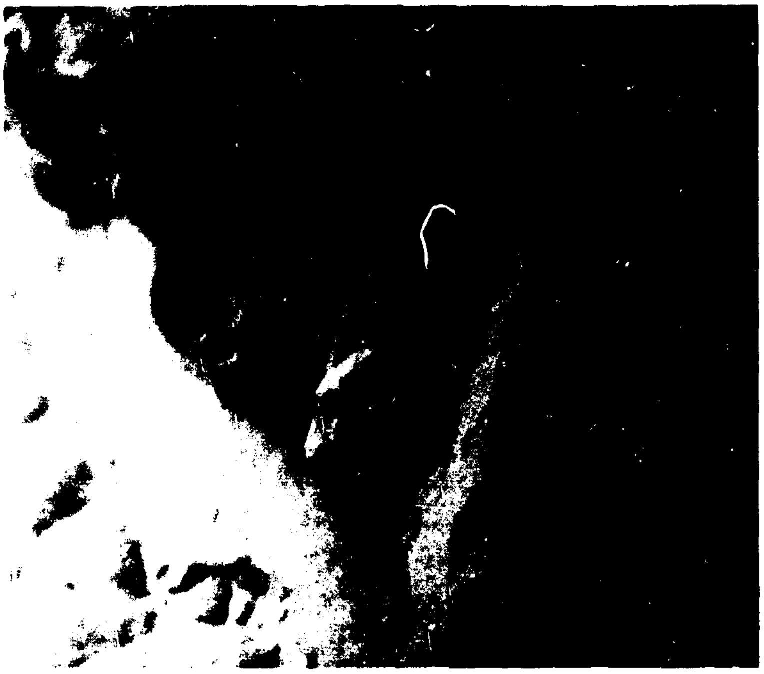


Figure 13. Plastic Flow Test Velocity 3229 ft/sec. Magnification 150 X.

Figure 14. Plastic Flow. Test Velocity 3229 ft/sec. Magnification 100 X.

Figures 15 and 16 show views of plastic flow that occurred on the surface of the specimen that was tested at an average velocity of 4202 ft/sec. It was pointed out in Section II that plastic flow on this specimen appeared to be less marked than that on the specimen tested at 3229 ft/sec. Markings, which suggest that there might be rifts in the surface of the aluminum test specimen, can be seen in Figure 16. The white structures in these photographs are the structures that appeared to be globules of a black deposit under the light microscope at low magnification. The fact that these structures collect a charge, and, therefore, appear white on inspection with the electron microscope, suggests that they are particles of a non-conducting material. It was suggested in Section II that they may be small particles of carbonized polyfoam; polyfoam was used to decelerate the rocket sled and the darkened appearance of this specimen suggests that it was subjected to a rather high temperature.

Figure 15. Plastic Flow. Test Velocity 4202 ft/sec. Magnification 100 X.

Figure 16. Plastic Flow. Test Velocity 4202 ft/sec. Magnification 200 X.

SECTION III

3. STUDY OF CROSS-SECTIONAL CUTS OF THE SPECIMENS TESTED AT VERY HIGH VELOCITIES

A cross section was cut on a diagonal through the center of each square specimen. Each cross-sectional cut was plated with nickel to reduce the rounding of edges that occurs during polishing. The cross sections were then mounted in plastic, polished, and etched[c]. The specimen tested at 4202 ft/sec was damaged in a mounting process and was eliminated from the study that is described in this section. Views of the cross-sectional cuts that were made are shown at 7X magnification in Figure 17. From the views shown in Figure 17, it can be seen that the nickel coating bonded very poorly to the aluminum specimen material although an effort was made to optimize the bonding by changing the current density. In the views shown in Figure 17, the residue of the nickel plate that did not flake off appears as discrete black globules along the surfaces of the cross-sectional cuts.

From the views of Figure 17, the increased degree of surface roughening that was produced as the impact velocity was increased from 1635 to 3229 ft/sec can readily be seen. Two studies were made with use of the cross-sectional cuts. One study was an investigation of the extent of work-hardening of the aluminum metal that was produced by the impinging drops. The other study was an investigation of the extent to which crack formation had progressed as a result of the drop impingement.

3.1 Work-Hardening of the Aluminum Metal

Knoop microhardness values using a 15-gram load were taken at various positions. To eliminate psychological bias, Knoop hardness values starting at the surface and then going to increased depths below the surface were established in a random manner rather than being taken at progressively greater depths. To avoid interference of the closely spaced numbers, they

[c] The metallurgical work for this study was done by Mr. Andrew R. Kraus of the Research Institute of the University of Dayton.

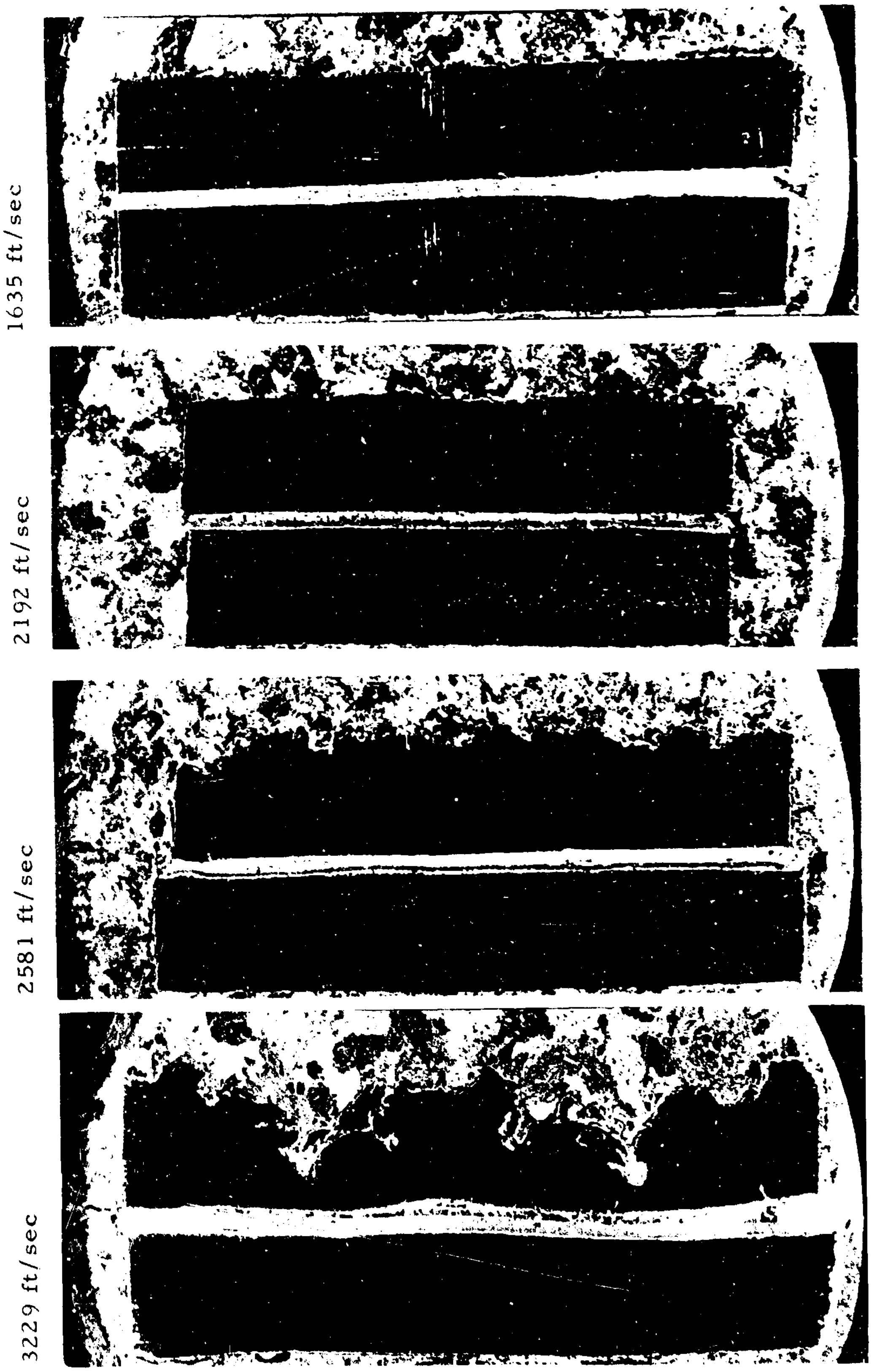


Figure 17. Cross-Sectional Cuts Of The Specimens

were taken along a zigzag path rather than in a straight line.

On the specimens tested at 1635 and 2192 ft/sec the Knoop microhardness values were consistently found to be about 35 with no increase at or near the surface. From this observation it can be concluded that either no work-hardening occurred as a result of waterdrop impacts against these specimens or that the heat that was engendered by the impacts was sufficient to anneal any hardening that did occur. The specimen tested at 2581 ft/sec showed a slight increase in hardness at the surface; this hardness decreased with depth below the surface to a value of about 35 at a depth of about 1 mm.

The largest number of hardness determinations were made on the specimen that was tested at 3229 ft/sec. Knoop microhardness values were established below a plateau, below two different valleys or depressions, and through the height of a hill or elevation. Values of hardness close to the surface were found to be as high as 49. There was no significant difference between the surface hardness on a hill or in a valley. The hardness decreased with depth below the surface.

Comparison of the hardness values found on the specimen tested at 2581 ft/sec with those found on the specimen tested at 3229 ft/sec indicates that there is no meaningful difference in the surface hardness reached or in the depth of layer that is hardened for this amount of increase in the impact velocity.

These observations suggest that the increase in surface hardness that takes place as impact velocity is increased is somewhat greater than the increase in the heat that is engendered by the impacts. The magnitude of the surface hardness produced by waterdrop impact against 1100 aluminum at 3229 ft/sec is a little less than that produced by a steel-sphere impact against 1100 aluminum at 570 ft/sec[10].

3.2 Search for Crack Formation

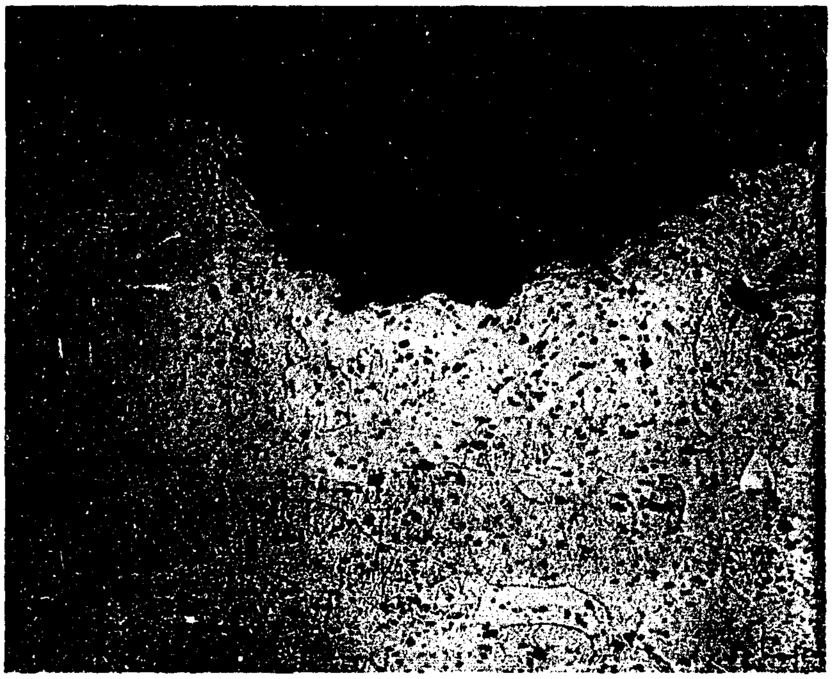
A search[c] for the existence of cracks in the cross-sectional

cuts of the specimens was made with use of the light microscope (metallograph). Micrographs taken at the sites of craters or depressions on the specimens tested at 1635 and 2192 ft/sec are shown in Figure 18 at a magnification of 250X. Some flattening of the surface grains can be seen in the views of Figure 18. However, no evidence at all that would suggest the existence of cracks was found at any point along the eroded surface of the cross sections taken from these specimens.

Inspection at 50 X of the specimen eroded at 2581 ft/sec revealed a structure that could possibly be the start of a crack. This is shown in view A of Figure 19. However, when the magnification was increased to 250 X. it was clear that this structure is not a crack at all but simply protruding metal that has been flattened against the surface by the impact of drops or by the radial flow of their liquid contents. The structure is shown at the higher magnification in view B of Figure 19. The lines of plastic flow in the metal clearly indicate the origin of this structure.

Inspection of the specimen tested at 3229 ft/sec at a magnification of 50X revealed several structures that suggested crack formation. These are shown in view A of Figures 20, 21, and 22. However, when the magnification was increased to 250X the lines of plastic flow in the metal clearly indicated that the meandering black lines are not cracks but are simply surfaces of separation between masses of plastically flowed metal.

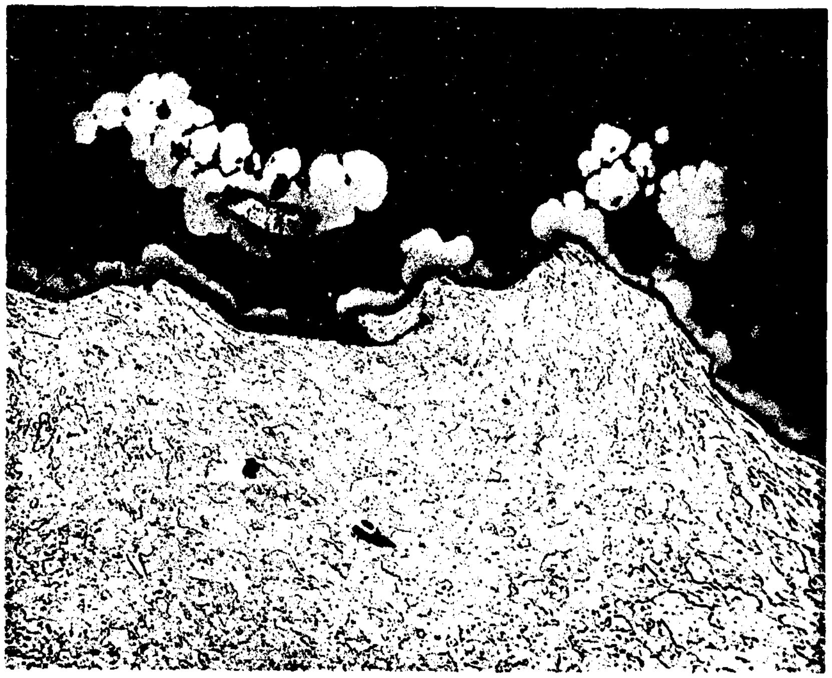
The tentative conclusion drawn from this limited study is that the surface of an aluminum specimen bombarded with waterdrops at a velocity as high as 3229 ft/sec is simply worked plastically by the stresses that are brought to bear. No cracks are formed as a result of the drop impacts.



View A. Test Velocity 1635 ft/sec Magnification 250 X.

View B. Test Velocity 2192 ft/sec Magnification 250 X.

Figure 18. Plastic Flow On Two Of The Test Specimens.

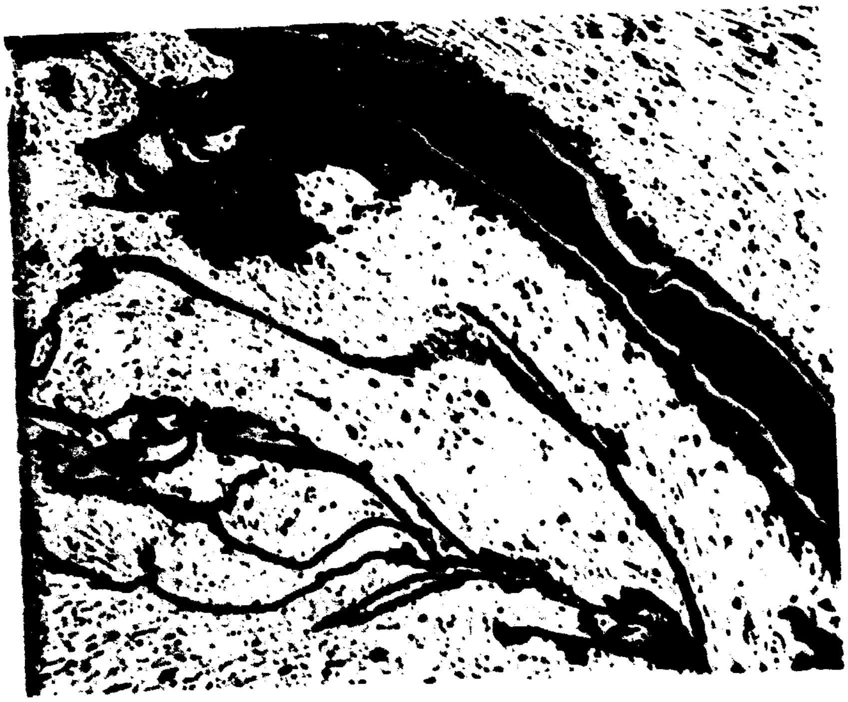


View A. Magnification 50 X.

View B. Magnification 250 X.

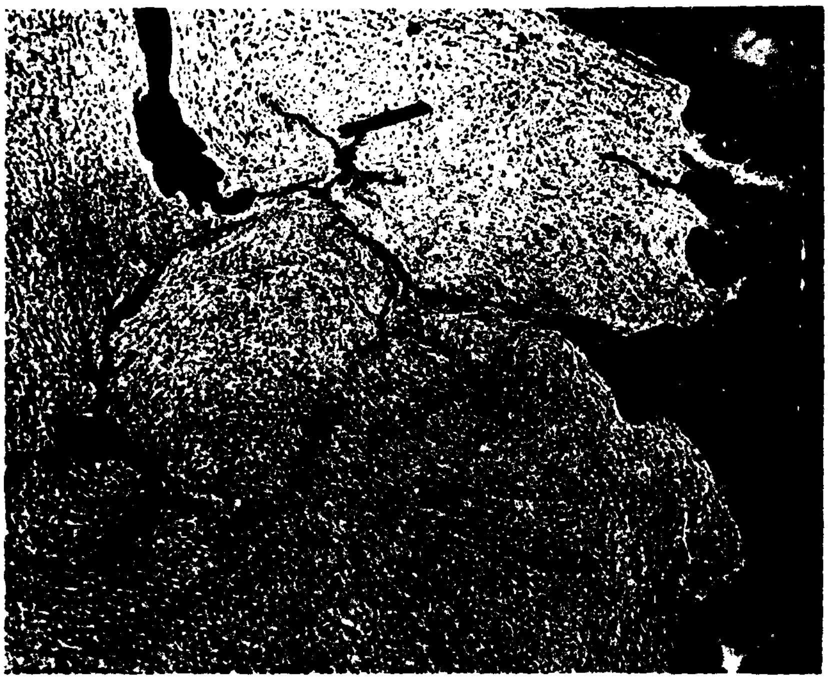
Figure 19. Plastic Flow. Test Velocity 2581 ft/sec.

View A. Magnification 50X



View B. Magnification 250 X.

Figure 20. Plastic Flow. Test Velocity 3229 ft/Sec.



View A. Magnification 50 X.

View B Magnification 250 X.

Figure 21. Plastic Flow. Test Velocity 3229 ft/sec.

View A. Magnification 50 X

View B. Magnification 250 X.

Figure 22. Plastic Flow. Test Velocity 3229 ft/Sec.

SECTION IV

4. POSTULATED MECHANISM OF WEIGHT LOSS OF 1100 ALUMINUM AS A RESULT OF DROP IMPACT AT VERY HIGH VELOCITIES

The study of cross-sectional cuts of 1100 aluminum specimens tested under waterdrop impingement at 1635, 2192, 2581, and 3229 ft/sec produced two conclusions: (1) An aluminum specimen bombarded with waterdrops at a velocity as high as 3229 ft/sec is simply worked plastically by the stresses that are brought to bear, and (2) very little work-hardening is produced as a result of the plastic working that occurs. These two conclusions are compatible if the amount of heat generated by the plastic flow of aluminum that occurs is sufficiently great to anneal the worked metal back to the O-state so that embrittlement cannot be accomplished. A substantial amount of heat is generated during the plastic flow of aluminum; it has been observed that aluminum spheres heat to the point of incandescence during hypervelocity impact at lower impact velocities than would be expected when comparison is made with copper spheres[11].

This self-annealing property of pure aluminum may make it a permanently plastic material as far as high-speed impacts are concerned. Without embrittlement, the formation of cracks is impossible. Without crack formation, the mechanism of material removal that depends upon circumscribing particles of the surface material with cracks cannot be applied. If embrittlement with consequent crack formation is prevented in aluminum by the heat that is generated during plastic flow, then the mechanism by which an aluminum specimen loses weight under high-speed drop impingement must be sought in its plastic behavior alone.

Rieger[5] has suggested that weight loss of a permanently plastic, non-work-hardenable material may be produced by the pinching off of protuberances that are formed as a consequence of plastic flow. Evidence of the existence of protuberances that could be broken off was found in the part of this study that is described in Section III. A material-removal process

that depends only on the breaking off of protuberances has a linear dependence on velocity because only one surface of severance is needed to reduce the volume of the test specimen by the volume of the protuberance (see Section 2. 5. 2. 4 of Ref. 4).

The average weight loss per unit area of two 1100 aluminum specimens tested under waterdrop impingement at velocities of 1635, 2192, 2581, 3229, and 4202 ft/sec with an impingement angle of 60 degrees are listed in Table 2 and plotted in Figure 23. The first three data points of this plot, which have been designated as regime I, do lie exactly on a straight line. However, at a velocity as high as 3229 ft/sec there is a very marked increase in weight loss which is inconsistent with the weight loss at lower velocities. The scanty evidence available suggests that the weight loss data collected at velocities of 3229 ft/sec or more belong to a mechanism of metal removal in which more than one surface of severance per eroded fragement volume is required. In the plot of Figure 23, this velocity range has been designated as regime II. Because only two data points are available in regime II, the velocity dependence is unknown; it has been tentatively indicated with a dashed line.

The subsurface structure of plastically flowed metal shown in Figures 20, 21, and 22 provides some insight into what the process of weight loss associated with regime II may consist of. In the view at 250X magnification shown in Figures 20, 21, and 22 it can be seen that the surface layer of metal has been severely worked by the pummeling action of the drop impacts at points where, as a shear consequence of probability, the most drops impinged. At these points the subsurface metal is no longer continuous; it is full of surfaces of discontinuity between individual masses of metal that have flowed in different directions. If test at 3229 ft/sec had been continued for a sufficiently long time, it is reasonable to expect that all of the surface metal over the entire face of the test specimen would be filled with such surfaces of discontinuity and that many of the individual masses of flowed metal would be completely circumscribed.

TABLE 2

Average Weight Loss per Unit Area of the Specimens Tested at an Angle of 60 Degrees

Impact Velocity ft/sec	Weight Loss per Unit Area for the Two Specimens Tested		
	Specimen 1 g/cm^2	Specimen 2 g/cm^2	Average g/cm^2
1635	0.0	0.0	0.0
2192	0.007	0.000	0.0035
2581	0.004	0.007	0.0055
3229	0.037	0.056	0.0465
4202	0.068	0.078	0.0730

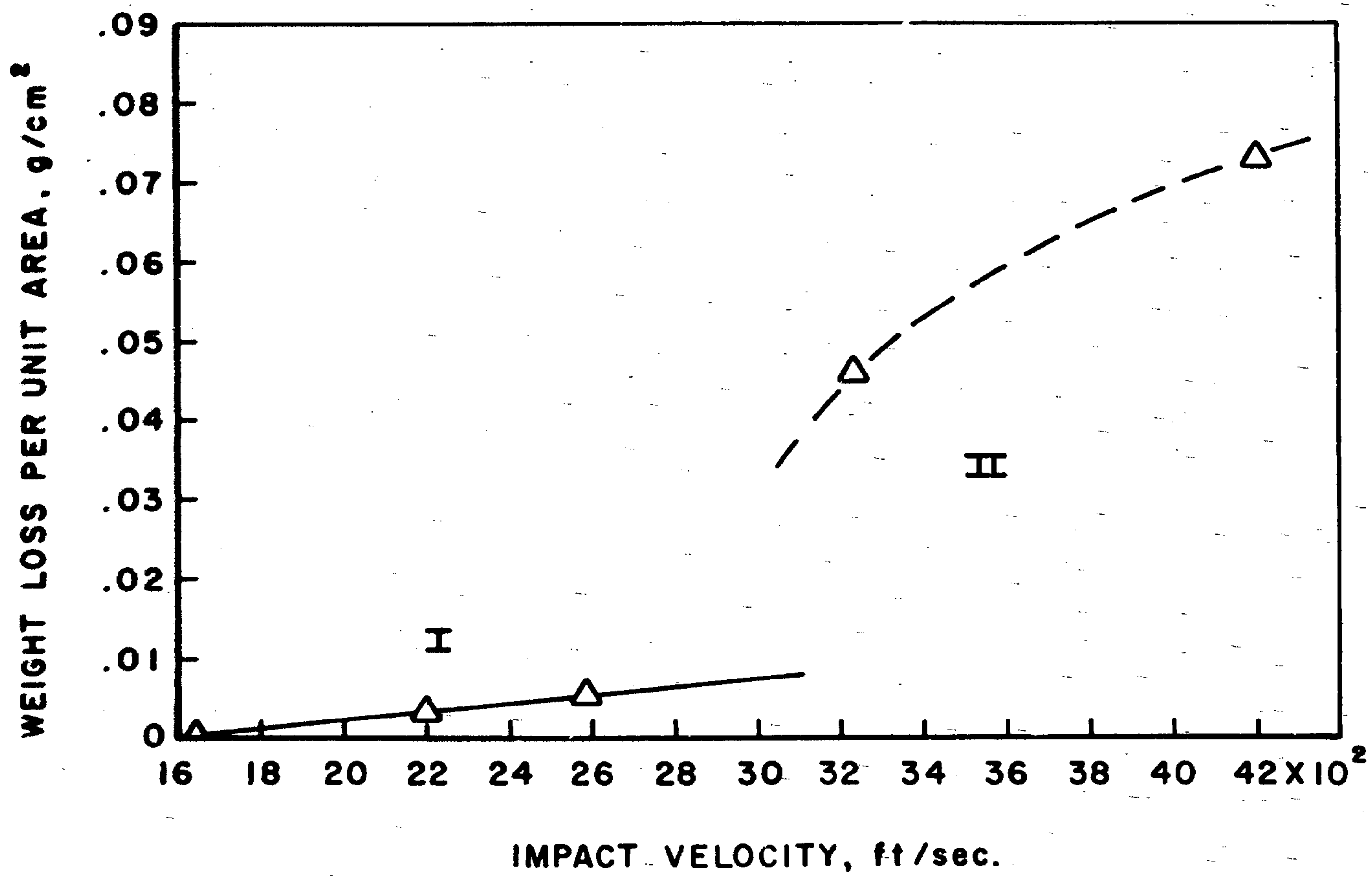


Figure 23. Average Weight Loss Per Unit Area Of The Specimens Tested At an Angle Of 60 Degrees.

In the sense described above, the pummeling effect of the individual waterdrop blows is a kind of comminution process in that it brings the metal into a quasi-dispersed state. A succeeding high-speed impact of a waterdrop against such a dispersed surface layer may literally extrude the separate masses of metal that are surrounded by surfaces of discontinuity.

This mechanism of weight loss can be expected to progress as a layer-removal process. That is, as soon as the original surface layer has been brought into a quasi-dispersed state and then extruded, a waiting period must occur during which the newly exposed underlayer material is brought into a quasi-dispersed state and extruded in its turn. The rate at which this type of layer removal is accomplished will be subject to the same statistical treatment as that which has already been applied to the layer removal of brittle materials as a consequence of crack formation and crack intersection[4]. In the case of brittle materials the physical picture is the circumscribing of individual sections of the surface layer with cracks. In the case of permanently plastic materials the physical picture is the circumscribing of individual sections of the surface layer with surfaces of separation. In each case, immediately after the original surface layer or any succeeding underlayer has been removed, there is a no-loss waiting period during which the newly exposed underlayer material is either filled with cracks or with surfaces of discontinuity.

The work-hardening capacities of aluminum and zinc are roughly equivalent and both very small[10]. Volume-loss data for zinc, which was tested under drop impingement at a velocity of 1000 ft/sec, were used in a partial test of the statistical model of erosion rate for brittle materials[12]. It was found that zinc differed from iron, nickel, and tantalum in that for zinc the number of impacts against the typical cell required to eject a layer of fragments was always the same. It is thought at this time that the very simple form of layer removal for which the counting-rule numbers are equal (N N N N etc.) may be a characteristic of a permanently plastic material whereas the more complex form of layer removal for which

the counting-rule numbers increase in size ($N_0 < N_1 < N_2 < N_3 <$ etc.) may be a characteristic of a material which has a substantial work-hardening capacity.

The question as to whether or not cracks can form in pure aluminum that is subjected to prolonged test under drop impingement at a velocity less than 1000 ft/sec has not been considered in the work described in this report.

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

The mechanism of erosion of pure aluminum under waterdrop impingement at velocities of Mach 1.5 and above is the result of plastic flow of the metal. The heat that is generated by the plastic flow that occurs is large enough to anneal the worked metal. The result of this is that embrittlement of the metal, which leads to crack formation, cannot occur.

There are two mechanisms by which erosive loss of the metal occurs in this velocity range. The first, which occurs at velocities up to Mach 2.5, is the breaking off of protuberances formed in the process of plastic flow. The second, which occurs at velocities above Mach 2.5, is the extrusion of separate masses of metal which have become surrounded by surfaces of discontinuity as a result of the repeated punching action of individual drop blows.

The second mechanism of metal loss can be expected to progress as a layer-removal process. It is recommended that accumulated weight-loss data be collected at a very high velocity and studied with use of the statistical model of erosion loss[4, 12] which has been developed.

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